

Giant Octupole Resonance Simulation

Rainer Walke, Klaus Morawetz

Fachbereich Physik, Universität Rostock, D-18051 Rostock, Germany

Using a pseudo-particle technique we simulate large-amplitude isoscalar giant octupole excitations in a finite nuclear system. Dependent on the initial conditions we observe either clear octupole modes or over-damped octupole modes which decay immediately into quadrupole ones. This shows clearly a behavior beyond linear response. We propose that octupole modes might be observed in central collisions of heavy ions.

Giant resonances regain much attention presently for the investigation of many particle effects in finite quantum systems. While most of the theoretical treatments of oscillations rely on the linear response method or RPA methods, large amplitude oscillations require methods beyond. Especially the question of the appearance of chaos is recently investigated [1–3]. The hypothesis was established that the octupole mode is overdamped due to negative curved surface and consequently additional chaotic damping [4–6]. Here we want to discuss at which conditions one might observe octupole modes at least in Vlasov - simulation of giant resonances.

We will consider different initial conditions of isoscalar giant resonances using a pseudo-particle simulation of Vlasov kinetic equation [7]. With a local potential $U(\mathbf{r})$ the quasi-classical Vlasov equation reads

$$\frac{\partial}{\partial t} f(\mathbf{p}, \mathbf{r}, t) + \frac{\mathbf{p}\hbar}{m} \nabla_{\mathbf{r}} f - \frac{1}{\hbar} \nabla_{\mathbf{p}} f \nabla_{\mathbf{r}} U(\mathbf{r}) = 0. \quad (1)$$

We represent the distribution function $f(\mathbf{p}, \mathbf{r}, t)$ by a sum of pseudo-particle distributions

$$f(\mathbf{p}, \mathbf{r}, t) \approx f_0(\mathbf{p}, \mathbf{r}, t) = \sum_{i=1}^{AN} \frac{1}{N} f_S(\mathbf{p} - \mathbf{p}_i(t), \mathbf{r} - \mathbf{r}_i(t)) \quad (2)$$

and use Gaussian pseudo-particles

$$f_S(\mathbf{p} - \mathbf{p}_i, \mathbf{r} - \mathbf{r}_i) = c e^{-(\mathbf{p} - \mathbf{p}_i)^2 / 2\sigma_p^2} e^{-(\mathbf{r} - \mathbf{r}_i)^2 / 2\sigma_r^2} \quad (3)$$

at \mathbf{r}_i with momentum \mathbf{p}_i [8]. These pseudo-particles follow classical Hamilton equations

$$\hbar \dot{\mathbf{p}}_i = -\nabla U, \quad \dot{\mathbf{r}}_i = \frac{\hbar \mathbf{p}_i}{m}. \quad (4)$$

We assume for the interacting nucleons a phenomenological density dependent Skyrme interaction [9] which results into the mean field

$$U(\varrho) = a \frac{\varrho}{\varrho_0} + b \left(\frac{\varrho}{\varrho_0} \right)^s \quad (5)$$

with $a = -356 \text{ MeV}$, $b = 303 \text{ MeV}$ and $s = 7/6$. The compression modulus is $K = 200 \text{ MeV}$. The evolution given by (1) is deterministic, fluctuations appear only due to numerical noise [10]. We are using 75 pseudo-particles

per nucleon and a pseudo-particle width, $\sigma_r = 0.53 \text{ fm}$, is adjusted so that the isovector giant dipole energy is reproduced at a single mass number. The experimental behavior of centroid energy with mass number is than reproduced. We have checked different numbers of test particles. The dependence of observables on the width is discussed in [11]. Numerically the ground state of nucleons is realized by Wood-Saxon shapes of density and Fermi spheres in momentum.

The distribution $n_a(\mathbf{p}) = \int d\mathbf{r} a_i f(\mathbf{p}, \mathbf{r})$ of mass distribution, $a_i = 1$, isospin, $a_i = \tau_i$, kinetic energy, $a_i = \frac{p_i^2}{2m}$, and kinetic isospin energy, $a_i = \frac{\tau_i p_i^2}{2m}$, is

$$n_a(p, \vartheta, \varphi) = \sum_{i=1}^{AN} \frac{(2\pi)^3}{N} a_i \frac{\delta(p - p_i)}{p_i^2} \delta(\varphi - \varphi_i) \frac{\delta(\vartheta - \vartheta_i)}{\sin(\vartheta_i)}. \quad (6)$$

Radial integration determines a spherical distribution

$$\bar{n}_a(\vartheta, \varphi) = \sum_{i=1}^{AN} \frac{1}{N} a_i \delta(\varphi - \varphi_i) \frac{\delta(\vartheta - \vartheta_i)}{\sin(\vartheta_i)}, \quad (7)$$

which can be decomposed into spherical harmonics

$$\bar{n}_a(\vartheta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^l a_{lm} Y_{lm}(\vartheta, \varphi), \quad (8)$$

$$a_{lm} = \sum_{i=1}^{AN} \frac{1}{N} a_i Y_{lm}^*(\vartheta_i, \varphi_i). \quad (9)$$

The observable distributions $\bar{n}_a(\vartheta, \varphi)$ are normalized to $\sqrt{4\pi} a_{00}$, i.e. to mass number A , total isospin T , kinetic energy E_{kin} and kinetic isospin energy E_{kinT} , respectively.

As a measure for the strength of the resonances we use

$$\hat{n}_a(\vartheta) = \int_0^{2\pi} d\varphi \bar{n}_a(\vartheta, \varphi) = \sum_{l=0}^{\infty} a_{l0} \sqrt{\frac{2l+1}{4\pi}} P_l(\cos \vartheta) \quad (10)$$

with Legendre polynomials P_l . The amplitudes of multipole moment, $a_{l0} \sqrt{\frac{2l+1}{4\pi}}$, will be displayed as a function of time in the following graphs. The value a_{10} means the dipole moment, vanishing for isoscalar resonances, a_{20} is characterizing the quadrupole oscillations and a_{30} the octupole ones.

As a first initial condition we use the ground state distribution of coordinates while the momentum distribution is deformed anisotropically. We have modified the momenta in a way which corresponds to a giant octupole mode. The local densities and currents remain the same as in ground state. Figure 1 shows that at start time $t = 0$ there is a pure giant octupole, which is damped out and a quadrupole resonance develops instead. The monopole and dipole amplitudes which should remain constant document the stability of simulation.

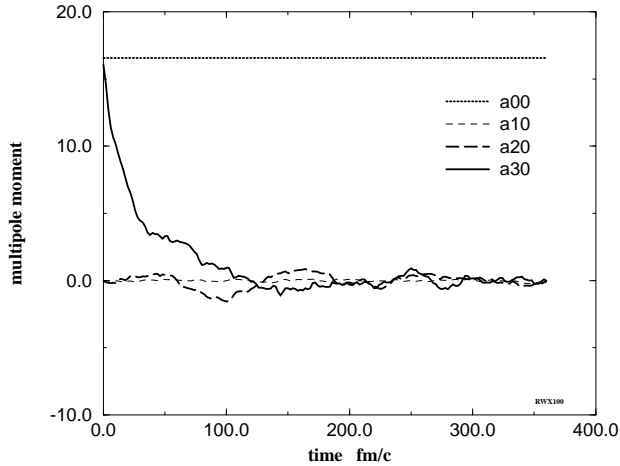


FIG. 1. The picture shows the time evolution of multipole moments $\sqrt{\frac{2l+1}{4\pi}}a_{l0}(t)$, $l = 0, 1, 2, 3$ of mass density concerning to normalization, dipole, quadrupole and octupole oscillation. Excitation is due to modification in momentum space only.

In agreement with the already mentioned hypothesis, the octupole mode is over-damped. The figure shows the nonlinear behavior of mode coupling. Within the linear response the damping rate is expected to be independent of initial conditions. We choose now other initial conditions to show that the result is very much dependent on initial conditions. Therefore we split the nucleus in two parts of mass ratio 3:7 in accordance with symmetry of the octupole oscillation and accelerate both pieces towards each other. Experimentally it might be realized as a central collision of two nuclei with corresponding masses. In figure 2 a clear quadrupole resonance appears and also a smaller octupole resonance can be seen. Both are damped out. Consequently there is no evidence for an over-damped octupole mode in this case.

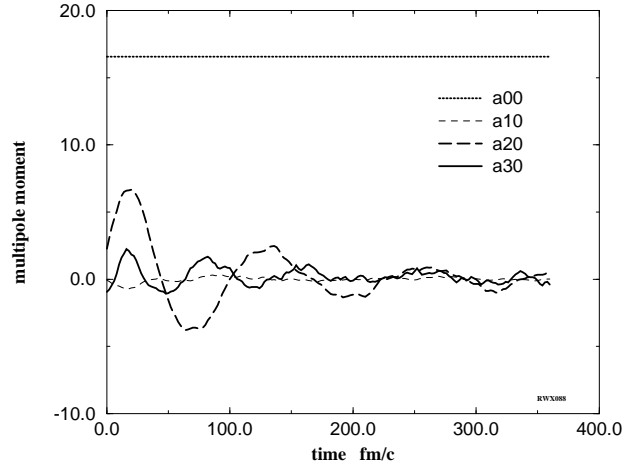


FIG. 2. This picture shows the time evolution of multipole moments $\sqrt{\frac{2l+1}{4\pi}}a_{l0}(t)$, $l = 0, 1, 2, 3$ of mass density. Excitation is due to asymmetric splitting (0.3 to 0.7) of the nucleus in two pieces using a plane in coordinate space. Then both pieces are accelerated towards each other.

In order to understand the different initializations, we split the kinetic energy into a thermal part and a collective part according to $\langle \mathbf{p}^2 \rangle = \langle (\mathbf{p} - \langle \mathbf{p} \rangle)^2 \rangle + \langle \mathbf{p} \rangle^2$. We analyze the time development of the total collective energy in the system

$$E_{coll}(t) = \frac{\hbar^2}{2m} \int d\mathbf{r} \varrho(\mathbf{r}) \langle \mathbf{p} \rangle^2(\mathbf{r}, t) \quad (11)$$

with the mean current

$$\langle \mathbf{p} \rangle(\mathbf{r}, t) = \frac{1}{\varrho(\mathbf{r})} \int \frac{d\mathbf{p}}{(2\pi)^3} \mathbf{p} f(\mathbf{p}, \mathbf{r}, t) \quad (12)$$

and the density

$$\varrho(\mathbf{r}, t) = \int \frac{d\mathbf{p}}{(2\pi)^3} f(\mathbf{p}, \mathbf{r}, t). \quad (13)$$

In figure 3 the development of collective energy can be seen. There is a background of about 50 MeV due to fixed correlations caused by finite width of pseudo-particles as one can see from the following estimation. Using (2) and (3) in (11) one obtains

$$\begin{aligned} E_{coll} &\approx \frac{1}{\varrho_0} \sum_{i=1}^{AN} \sum_{j=1}^{AN} \frac{1}{N^2} p_i p_j \\ &\quad \times \int dr f_S(r - r_i(t), \sigma_r) f_S(r - r_j(t), \sigma_r) \\ &\approx \frac{1}{\varrho_0} \sum_{i=1}^{AN} \sum_{j=1}^{AN} \frac{1}{N^2} p_i p_j f_S(r_i(t) - r_j(t), \sqrt{2}\sigma_r) \\ &\geq \frac{1}{\varrho_0 N} \frac{1}{(\sqrt{2\pi}\sqrt{2}\sigma_r)^3} \sum_{i=1}^{AN} \frac{1}{N} p_i. \end{aligned} \quad (14)$$

For simulation parameter of ^{208}Pb , $\rho_0 = 0.162 \text{ fm}^{-3}$, $N = 75$, $\sigma_r = 0.53 \text{ fm}$, we obtain a basic collective energy of 54 MeV. Using more testparticles would diminish this level.

The solid line corresponding to figure 1 shows no initial collective energy. The exclusive initial excitation in momentum space without correlation in spatial domain leads to zero initial collective energy. This correlations are forming during time evolution. Of course, there is no center of mass motion, otherwise we would see just the mean streaming velocity.

This situation is changed if we use the second preparation with simple momentum-space-correlations. The long dashed line in figure 3 shows initial collective correlations corresponding to figure 2. Since we can deposit enough collective energy in this case, we observe a clear octupole motion.

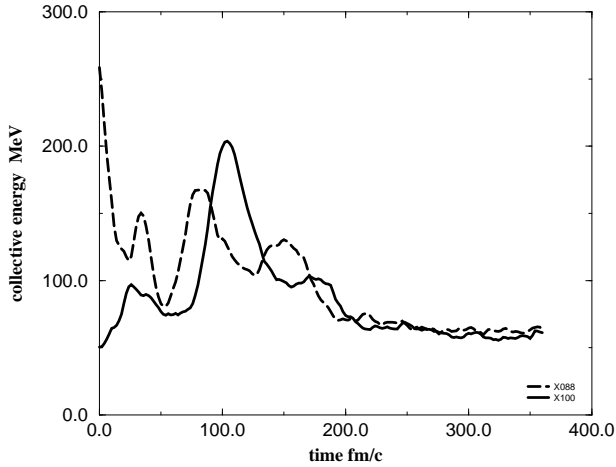


FIG. 3. The time evolution of collective energy. The solid line corresponds to the excitation scheme of figure 1 and the long dashed line corresponds to the figure 2, respectively. While the first starts without collective energy, the second one starts with maximal collective energy.

In order to compare with [5] we calculate the adiabaticity index η defined in [5] as the ratio of maximum radial surface velocity to the maximum particle speed. A smaller ratio denotes a more adiabatic shape changes in relation to the particle speed. In analogy we define such index as a ratio

$$\eta = \frac{\frac{\partial}{\partial t} \sqrt{\langle r^2 \rangle}(\vartheta)}{v_F} \quad (15)$$

of the root mean square radius speed in forward direction (opening angle ϑ) and the Fermi velocity. With opening angle 0.4 rad we obtain a maximum $\eta = 0.12$ for figure 1 and $\eta = 0.30$ for figure 2. This shows that we are essentially still in the adiabatic regime described in [5].

The nonlinear behavior described so far already documents that we are in a regime of large amplitude os-

cillations where linear response fails. The corresponding radius elongation in coordinate space varies about 10 %.

To summarize, we have observed octupole resonances in finite nuclei dependent on the initial configuration. The appearance of an octupole mode was shown to be possible by correlating the spatial and momentum initial excitation. It is possible to excite an octupole mode with sufficient collective energy deposited initially. We suggest that isoscalar giant octupole resonances should be possible to observe in nuclear collisions of mass ratio about 3:7 corresponding to octupole symmetry. For a mass ratio of e.g. 1:1 we observe no octupole resonance in simulation.

The fruitful discussions with Peter Schuck and P. Lipavský are gratefully acknowledged. This work was supported by a grant (R.W.) and project No. 44185 from the Max-Planck-Gesellschaft.

-
- [1] W. Bauer, D. McGrew, V. Zelevinsky, and P. Schuck, Phys. Rev. Lett. **72** (1994) 3771
 - [2] G.F. Burgio, M. Baldo, A. Rapisardo, P. Schuck, Phys. Rev. **C52** (1995) 2475
 - [3] K. Morawetz, Phys. Rev. **C55** (1997) R1015
 - [4] C. Jarzynski, W.J. Swiatecki, Nucl. Phys. **A552** (1993) 1
 - [5] J. Blocki, J.-J. Shi, W.J. Swiatecki, Nucl. Phys. **A554** (1993) 387
 - [6] J. Blocki, J. Skalski, W.J. Swiatecki, Nucl. Phys. **A816** (1997) 1
 - [7] G. F. Bertsch, S. Das Gupta, Phys. Rep. **160** (1988) 189
 - [8] C.-Y. Wong, Phys. Rev. **C25** (1982) 1460
 - [9] M. Colonna, M. Di Toro, A. Guarnera, Nucl. Phys. **A589** (1995) 160
 - [10] M. Colonna, G.F. Burgio, Ph. Chomaz, M. Di Toro, J. Randrup, Phys. Rev. **C 47** (1993) 1395
 - [11] K. Morawetz, R. Walke, Phys. Rev. C sub., nucl-th/9807045